# Optimal Transmit Power and Packet Size in Wireless Sensor Networks in Shadowed Channel

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***Abstract* - This paper investigates the effects of shadowing on the optimal transmit power required to sustain the network connectivity while maintaining a predefined maximum tolerable Bit Error Rate (BER) in a Wireless Sensor Networks (WSN). Optimization of transmit power is of great importance in WSN since sensor nodes are battery driven and optimization helps to increase battery life by reducing inter node interference significantly. An infinite Automatic Repeat Request (ARQ) model has been considered to assess the impact of shadowing and other network conditions on energy requirement for successful packet transmission in WSN. We also find the optimal packet length based on energy efficiency. Effects of shadowing on optimal packet size and energy efficiency in packetized data transmission are also investigated. Further energy consumption is minimized considering a variable packet length based transmission. Use of optimal packet size shows a significant reduction in energy spending.**

***Keywords* -Wireless Sensor Networks, BER, Optimal transmit power, Optimal packet size, ARQ, Shadowing.**

## 1. INTRODUCTION

Most of the research work on WSN assumes idealized radio propagation models without considering fading and shadowing effects. However network performance degrades due to shadowing and fading. Energy conservation is one of the most important issues in WSN, where nodes are likely to rely on limited battery power. The connectivity of WSN mostly depends on the transmission power of the source nodes. If the transmission power is not sufficiently high there may be single or multiple link failure. Again transmitting at high power reduces the battery life and introduces excessive inter node interference. So an optimal transmit power is required for each node to preserve the network connectivity and prolong network lifetime. Different network conditions have significant impact on optimal transmit power. Most of the previous research work in this field assumes free-space radio link model and Additive White Gaussian Noise (AWGN) [1-3]. However shadow fading has significant impact on network performance. So, it is important to investigate optimal transmit power required to maintain the network connectivity in shadowed environment. Several approaches have been proposed in literature to prolong network lifetime. Sooksan et al. [1] evaluated Bit Error Rate (BER) performance and optimal power to preserve the network connectivity considering only path-loss and thermal noise. In [2] Bettstetter et al. derived the transmission range for which network is connected with high probability considering free-space radio link model. In [3] the relationships between transmission range, service area and network connectedness is studied in a free space model. Narayanaswamy et al. [4] proposed a protocol that extends battery life through providing low power routes in a medium with path loss exponent greater than 2. In [5] a minimum uniform transmission power of an ad hoc wireless network to maintain network connectivity is proposed considering path loss only.

In this paper optimal transmit power is derived in shadowed channel while maintaining a certain maximum tolerable BER. Since performance of WSN is likely to be affected by shadowing, it is important to investigate the impact of shadowing on optimal power. The optimal power in presence of shadowing also depends on routing and the Medium Access Control (MAC) protocol used [1, 6-7]. In the present work we carry out simulation studies to derive the optimal transmit power in presence of shadowing for a network model employing square grid topology as in [1]. Optimal transmit power is evaluated under several conditions of network such as node density, data rate and different level of shadow fading.

Here energy level performance of a square grid sensor network is also studied in presence of shadowing [8-10]. We consider an infinite ARQ model to successfully transmit a packetized data from one node to another node. A data packet is retransmitted infinitely till it is successfully received [8]. It is assumed that the ACK / NAK from receiving node are instantaneous and error free. We estimate energy efficiency of the network under different level of shadowing and node spatial density. A scheme based on variable packet size is also evaluated. In this scheme packet size corresponds to highest energy efficiency is used. This packet size, which contributes maximum efficiency, is called optimum packet length. Impact of



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shadowing on optimal packet size is investigated. Use of optimal packet length based transmission shows significant reduction in energy spent compared to a fixed packet based transmission. Thus use of optimal packet based transmission is seen to enhance network lifetime.

The rest of the following paper organized as follows: In Section II, we describe the System Model and assumptions that are used in the derivation of optimal transmit power and optimal packet size in the presence of shadowing. Section III shows simulation results and discussions. Finally conclusions are drawn in Section IV.

## II. SYSTEM MODEL

We consider a topology of network as presented in [1]. Figure 1 shows a two tier sensor network using square grid topology [1, 8]. Distance between two nearest neighbor is

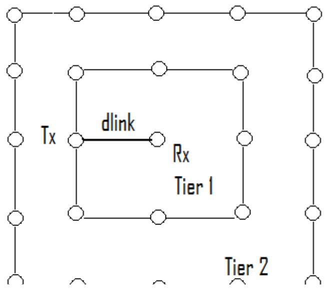


Fig. 1: Sensor nodes in square grid topology.

$d_{link}$. It is assumed that N numbers of nodes are distributed over a region of area A obeying square grid topology. The node spatial density $\rho_{sq}$ is defined as number of nodes per unit area i.e., $\rho_{sq} = N/A$. The minimum distance between two consecutive neighbors is given by

$$d_{link} = \frac{\sqrt{N}}{\sqrt{N}-1} \times \frac{1}{\sqrt{\rho_{sq}}} \qquad (1)$$

When the node density increases, minimum distance between two nodes decreases following equation (1). Here we assume a simple routing strategy such that a packet is relayed hop-by-hop, through a sequence of nearest neighboring nodes, until it reaches the destination [6]. Therefore, we assume that a route between source and destination exists. Infinite ARQ is considered between the pair.

Here we consider a simple reservation-based MAC protocol, called reserve-and-go (RESGO) following [1, 7]. In this protocol, a source node first reserves intermediate nodes on a route for relaying its packets to the destination. A transmission can begin after a route is discovered and reserved. If the destination node is busy, it waits for an exponential random back-off time before transmit or relay each packet. When the random back-off time expires, node starts transmitting a packet. The random back-off time helps to reduce interference among nodes in the same route and also among nodes in different routes. Throughout this paper, we assume that the random back-off time is exponential with mean $1/\lambda_t$, where $\lambda_t$ is the packet transmission rate.

The major perturbations in wireless transmission are large scale fading and small scale fading [9-10]. Large scale fading represents the average signal power attenuation or path loss due to motion over large areas. This phenomenon is affected by prominent terrain contours (hills, forests, billboards, clumps of buildings, etc.) between the transmitter and receiver. The receiver is often represented as being "shadowed" by such prominences. The statistics of large-scale fading provide a way of computing an estimate of path loss as a function of distance. This is described in terms of a mean-path loss (nth-power law) and a log-normally distributed variation about the mean [10]. In the presence of shadowing, with a T-R separation of d, the path loss $PL(d)$ at a particular location is random and distributed log-normally about the mean distance dependent value of $\overline{PL}(d)$ [9]

$$PL(d)\big|_{dB} = \overline{PL}(d)\big|_{dB} + X_\sigma \qquad (2)$$

where $X_\sigma$ denotes a zero mean, Gaussian random variable with standard deviation σ. Thus the received signal power can be expressed as

$$P_{sw}(d)\big|_{dBm} = G_t\big|_{dB} + G_r\big|_{dB} + P_{Tx}\big|_{dBm} - \left(\overline{PL}(d)\big|_{dB} + X_\sigma\right) \qquad (3)$$

where $P_{sw}$ is the received signal power in shadowed environment, $P_{Tx}$ is the transmit power, $G_t$ and $G_r$ are the transmitting and receiving antenna gain respectively. Here we consider omni directional $(G_t = G_r = 1)$ antennas at the transmitter and receiver. The carrier frequency is in the unlicensed 2.4 GHz band.

It can be assumed without loss of generality that source node is at the center of the network (see Fig. 1). If a destination node is selected at random, the minimum number of hops to reach the destination can vary from 1 to $2i_{\max}$, where $i_{\max}$ is the maximum tier order. Counting the number of hops on a route from the source to each destination node and finding the average value we determine the average number of hops. Using average number of hop we can evaluate the total energy required to successfully deliver a packet from source to a final destination following equation (21). Assuming that each destination is equally likely, the average number of hops on a route can be written as [1]



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$$\bar{n}_{hop} \cong \sqrt{N}/2 \qquad (4)$$

The received signal at the receiver is the sum of three components (i) the intended signal from a transmitter, (ii) interfering signals from other active nodes, and (iii) thermal noise. Since the interfering signals come from other nodes, we assume that total interfering signal can be treated as an additive noise process independent of thermal noise process. The received signal $S_{rcv}$ during each bit period can be expressed as [1]

$$S_{rcv} = S_{sw} + \sum_{j=1}^{N-2} S_j + n_{thermal} \qquad (5)$$

where $S_{sw}$ is the desired signal in shadowed channel, $S_j$ is the interference from other nodes and $n_{thermal}$ is thermal noise signal.

Assuming Binary Phase Shift Keying (BPSK) modulation, there can be two cases for the amplitude of the $S_{sw}$

$$S_{sw} = \sqrt{\frac{P_{sw}}{R_{bit}}} = \sqrt{E_{bit}} \text{ for a } +1 \text{ transmission}$$
$$= -\sqrt{\frac{P_{sw}}{R_{bit}}} = -\sqrt{E_{bit}} \text{ for a } -1 \text{ transmission}$$
$$(6)$$

where $\sqrt{E_{bit}}$ is the bit energy of the received signal in the presence of Rayleigh fading. The interference power received from node $j$ can be written using Frii's transmission equation [6,9-10]

$$P_{\text{int}\,j} = \frac{P_{Tx} G_t G_r \lambda^2}{(4\pi)^2 d_{link}^{\alpha} v_j^{\alpha}} \qquad (7)$$

$v_j$ is the multiplicative factor depends on the position of the interfering node. For example, the node at the corner of the second tier (Fig.1) is at a distance $2\sqrt{2}d_{link}$ with respect to the center. So, in this case the multiplicative factor is $v_j = 2\sqrt{2}$. It is observed that the significant part of the inter-node interference comes from the first two tires only. So we consider inter-node interference from first two tires only.

For each interfering node $j$, the amplitude of the interfering signal can be of three types [1]:

$$S_j = \sqrt{\frac{P_{int\,j}}{R_{bit}}} \text{ for a } +1 \text{ transmission}$$
$$= -\sqrt{\frac{P_{\text{int}\,j}}{R_{bit}}} \text{ for a } -1 \text{ transmission}$$
$$= 0 \text{ for no transmission of node } j \qquad (8)$$

The probability that an interfering node will transmit and cause interference depends on the MAC protocol used. Considering the RESGO MAC protocol and assuming that each node transmits packets with length $L_{packet}$, the interference probability is equal to the probability that an interfering node transmits during the vulnerable interval of duration $L_{packet}/R_{bit}$, where $R_{bit}$ is the bit rate. This probability can be written as [7]

$$p_{trans} = 1 - e^{-\frac{\lambda_t L_{packet}}{R_{bit}}} \qquad (9)$$

Thus $S_j$ appears with different probabilities of transmission as given below

$$S_j = \sqrt{\frac{P_{\text{int}\,j}}{R_{bit}}} \text{ with probability } \frac{1}{2}P_{trans}$$
$$= -\sqrt{\frac{P_{\text{int}\,j}}{R_{bit}}} \text{ with probability } \frac{1}{2}P_{trans}$$
$$= 0 \text{ with probability } (1 - P_{trans}) \qquad (10)$$

The thermal noise power can be written as

$$P_{thermal} = FkT_0B \qquad (11)$$

where $F$ is the noise figure, $k = 1.38\times10^{-23} J/K$ is the Boltzmann's constant, $T_0$ is the room temperature and $B$ is the transmission bandwidth. The received thermal noise signal is simply

$$n_{thermal} = \sqrt{FkT_0B} \qquad (12)$$

Size of the interference vector $S_j$ increases as the number of nodes increases in the network. As interference from the first two tiers is significant, we consider the interference from the first two tires only.

Next we derive the energy spent in successfully transmitting a data packet considering infinite ARQ between a pair of transmitting and receiving nodes. It is assumed that each packet consists of header, message and trailer as shown in Fig. 2. So, transmitted packet length can be expressed as [11],

$$L_{packet} = l_h + l_m + l_t \qquad (13)$$


Fig. 2: Simple structure of a packet



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where $l_h$, $l_m$ and $l_t$ are the header length, message length and trailer length respectively. So, the energy required to transmit a single packet is

$$E_{Tx} = \frac{P_{Tx} L_{packet}}{R_{bit}} \tag{14}$$

Here it is assumed that 75% of the transmit energy is required to receive a packet [12]. So, energy required to communicate, i.e. transmit and receive a single packet is given by

$$E_{packet} = \frac{P_{Tx}(L_{packet} + l_{ack})}{R_{bit}} \times 1.75 + E_d \tag{15}$$

where $E_d$ is the decoding energy to decode a single packet and $l_{ack}$ is the acknowledge frame length. Since Forward Error Correction (FEC) technique is not used here, decoding energy and trailer length both are assumed zero [11]. Thus the energy to communicate a single packet is:

$$E_{packet} = \frac{P_{Tx}(l_h + l_m + l_{ack})}{R_{bit}} \times 1.75 \tag{16}$$

The minimum energy required to communicate a packet is the energy required to transmit and receive the message bits ($l_m$) only. This minimum energy can be derived by the following expression:

$$E_{\min} = \frac{P_{Tx} l_m}{R_{bit}} \times 1.75 \tag{17}$$

Now we consider an infinite ARQ scheme where a data packet is retransmitted infinitely until it is received successfully. The average number of retransmission, $n_{retrans}$ can be expressed by the following expression

$$n_{retrans} = \sum_{i=1}^{\infty} PER_{link}^{i} \cong \frac{1}{\frac{1}{PER_{link}} - 1} \tag{18}$$

where $PER_{link}$ is the packet error rate in a single hop. So, the energy spent to successfully deliver a packet is given by

$$E_{packet}^{ARQ} = \frac{P_{Tx}(l_h + l_m + l_{ack})}{R_{bit}} \times 1.75 \times (1 + n_{retrans}) \tag{19}$$

Thus the total energy spent to successfully deliver a packet from source to destination is give by

$$E_{route} = \bar{n}_{hop} \times E_{packet}^{ARQ} \tag{20}$$

Now the energy efficiency $(\eta)$ is expressed as [12]:

$$\eta = \frac{E_{\min}}{E_{packet}^{ARQ}} = \frac{l_m}{(l_h + l_m + l_{ack})(1 + n_{retrans})} \tag{21}$$

Next we present our simulation results based on above system model.

## III. Results and Discussion

Table 1 shows the important network parameters used in the simulation study

TABLE 1

Network Parameters used in the Simulation

| Parameter | Values |
|---|---|
| Path loss exponent ($\gamma$) | 2 |
| Number of nodes in the network (N) | 289 |
| Node spatial Density ($\rho_s$) | $10^{-7}$ |
| Packet arrival rate at each node ($\lambda_t$) | 0.5 pck/s |
| Career frequency ($f_c$) | 2.4 GHz |
| Noise figure (F) | 6dB |
| Room Temperature ($T_0$) | 300k |
| Transmission Power ($P_{Tx}$) | 1mW, 100mW |

Fig. 3 shows route BER as a function of node spatial density. It is observed that $BER_{route}$ performance improves with the increase in node spatial density. However it is seen that beyond a certain node density the $BER_{route}$ does not change with further increase in node spatial density and a floor in $BER_{route}$, as denoted by $BER_{floor}$ appears. The desired signal power as well as the inter-node interference increases with increase in node density. As a result we obtain the $BER_{floor}$. This is expected because, increasing node spatial density beyond a certain limit no longer improves the signal to noise ratio (SNR), as the interfering nodes also become close enough to the receiver. It is seen that $BER_{route}$ performance degrades in shadowed channel. This is because in shadowed environment signal to interference noise ratio (SNIR) degrades. For a data rate of 5 Mbps and node spatial density of $1.4 \times 10^{-4}$ $BER_{route}$ is $6.2 \times 10^{-4}$ without shadowing while it is $3.7 \times 10^{-2}$ in shadowed channel of standard deviation σ = 8 dB

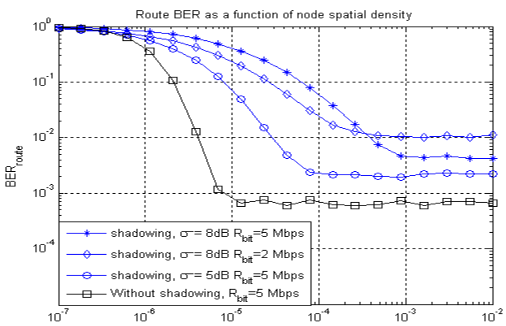


Fig 3: Route BER as a function of node spatial density with and without the presence of shadowing for two different level of shadowing.



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under same data rate and node spatial density. It is also observed that with increase in severity of shadowing, i.e., as σ increases from 5 dB to 8 dB, $BER_{route}$ performance degrades. It is also seen that $BER_{route}$ degrades as bit rate decreases. This is due to increase in vulnerable interval with decrease of bit rate [7]. As a result, transmission probability of the interfering nodes increases.In Fig. 4, we compare the optimal common transmit power as a function of bit rate in the presence of shadowing and without considering shadowing. Optimal common transmit power is the minimum power sufficient to preserve network connectivity while satisfying a predefined BER threshold ($BER_{th}$) value at the end of a multihop route. Here variation

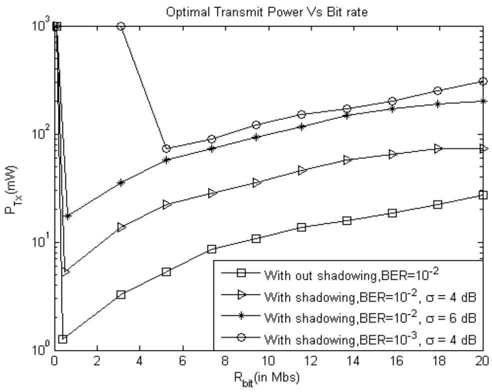


Fig 4: Optimal Power as a function of Bit Rate for different BER threshold at a node spatial density of $10^{-6}$.

of optimal transmit power with bit rate is shown for various values of $BER_{th}$. It is seen that optimal transmit power increases as the data rate increases. It is mainly because of the high thermal noise introduced due to high bit rate. It is observed that optimal transmit power required to transmit a data packet in the presence of shadowing is higher than the power required in absence of shadowing for same data rate. For example at a bit rate of 5 Mbps and $BER_{th} = 10^{-2}$, the optimal transmit power is 5.3 mW without shadowing. However for the same $BER_{th}$ and data rate the optimal transmit power is increased to 22.1 mW in presence of shadowing with standard deviation 4 dB. As shadowing increases, in order to maintain connectivity with same level of $BER_{th}$, transmit power also needs to be increased so as to compensate the higher level of shadowing. It is seen from Fig. 4 that there is a critical data rate, below which the desired $BER_{th}$ cannot be satisfied for any level of transmit power. The critical bit rate occurs at the point where the $BER_{floor}$ for that particular data rate becomes higher than the desired $BER_{th}$. Further it is seen that critical bit rate increases with the increase in severity of shadowing.

Fig. 5 shows the energy efficiency as a function of packet length for various level of shadowing and node spatial density. It is seen that efficiency attains a peak value at a given packet size. The message length corresponding to maximum efficiency is optimal packet size from energy efficiency perspective [11-12]. Thus there exists an optimal packet size for a particular network condition. It is seen that the energy efficiency shows a steep drop for message lengths smaller than the optimal length. This behavior can be attributed to the higher overhead and start-up energy consumption of smaller

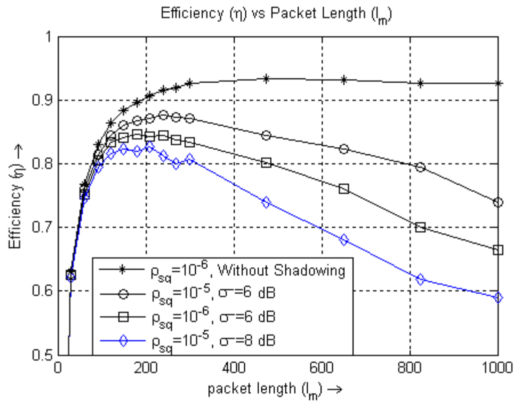


Fig. 5: Efficiency as a function of packet length for different node spatial density and shadowing environment.

packets [11]. On the other hand, for message length larger than the optimal length, the drop in energy efficiency is much slower due to increase in average retransmission. With the increase in packet length the vulnerable interval increases and the probability of transmission of an interfering node becomes high. It is observed that efficiency degrades with the increase in severity of shadowing. This is because with increase in severity of shadowing the SNIR degrades. This results in more number of retransmissions for successful delivery of a packet. Thus the energy spent per packet increases, which reduces energy efficiency. Further the optimum packet length decreases with the increase in severity of shadowing. For example as shadow fading increases from σ= 6dB to σ=8dB, size of optimal packet reduces from 240 bit to 150 bit for a node spatial density of $10^{-5}$. It is also seen that energy efficiency improves with increase in node spatial density. Further the optimal packet length increases with increase in node spatial density. Any packet size except optimal size deteriorates the efficiency.

Fig. 6 shows the comparison of energy requirement for successfully transmission of a file of size 122 Kbyte in two cases – (i) a fixed packet length and (ii) an optimal packet size. In the first case we evaluate energy for two different typical fixed packet lengths i.e. 1000 bit and 500 bit. In the second case we use optimal packet length corresponding to that particular node spatial density as obtained from Fig. 5. It is observed that use of optimum packet size reduces the energy requirement significantly. In case of optimum packet size, less number of retransmissions is required as compared to a fixed packet size case. For example, at a node spatial density of $4.3\times10^{-5}$ and bit rate of 5 Mbps, the use of optimum packet size reduces energy



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requirement by an amount of 13.5% as compared to a fixed packet size of 1000 bit. The optimal packet size shows excellent performance in the low node spatial density region. For example, at node spatial density of $4\times10^{-7}$ the required energy is 40 mJ for optimum packet length based transmission, while it is 90 mJ for a transmission based on a fixed packet length of 500 bit.

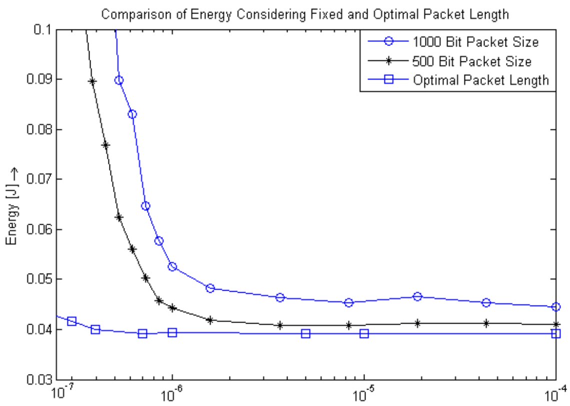


Fig. 6: Energy consumption as a function of node spatial density using fixed and optimal packet size at a bit rate of 5 Mbps and σ = 4 dB.

## IV. Conclusion

In this paper we have investigated the optimal transmit power and optimal packet length for wireless sensor networks in lognormal shadowed channel. It is observed that optimal transmit power required to maintain network connectivity satisfying a given maximum acceptable BER threshold value in the presence of shadowing is more as compared to that in absence of shadowing. It is also seen that optimal transmit power increases with increase in severity of shadowing. The BER performance degrades with increase in severity of shadowing. An optimum packet length, which maximizes energy efficiency, is also derived. The optimum packet size decreases with the increase in severity of shadowing. Further it is seen that optimal packet length increases with the increase in node spatial density. It is also seen that transmission based on optimum packet saves energy significantly and enhances network lifetime. Further energy efficiency degrades with the increase in severity of shadow fading and decrease of node spatial density. Thus shadowing has significant impact on choice of optimal power and optimal packet size which enhances lifetime of network.

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